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Gaze behaviour in audiovisual speech perception: Asymmetrical distribution of face-directed fixations

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Abstract. Speech perception under natural conditions entails integration of auditory and visual information. Understanding how visual and auditory speech information are integrated requires detailed descriptions of the nature and processing of visual speech information. To understand better the process of gathering visual information, we studied the distribution of face-directed fixations of humans performing an audiovisual speech perception task to characterise the degree of asymmetrical viewing and its relationship to speech intelligibility. Participants showed stronger gaze fixation asymmetries while viewing dynamic faces, compared to static faces or face-like objects, especially when gaze was directed to the talkers' eyes. Although speech perception accuracy was significantly enhanced by the viewing of congruent, dynamic faces, we found no correlation between task performance and gaze fixation asymmetry. Most participants preferentially fixated the right side of the faces and their preferences persisted while viewing horizontally mirrored stimuli, different talkers, or static faces. These results suggest that the asymmetrical distributions of gaze fixations reflect the participants' viewing preferences, rather than being a product of asymmetrical faces, but that this behavioural bias does not predict correct audiovisual speech perception.

1 Introduction

Speech perception under natural conditions entails the integration of auditory and visual information. Although speech research has been focused on auditory processing, visual information plays a vital role in communication and can affect perceived speech (eg Sumby and Pollack 1954; McGurk and MacDonald 1976). It is, however, not clear what visual information is important and what influences the gathering of this information. Studies of gaze behaviour have shown that fixation distribution varies with different environmental and social contexts (Vatikiotis-Bateson et al 1998; Lansing and McConkie 1999, 2003; Buchan et al 2007). One unresolved question is the role of cerebral asymmetry in audiovisual speech perception.

In spite of the general symmetry of the human body, our morphology and behaviour are not left – right equivalent on a more detailed scale (Palmer and Strobeck 1986). Hemispheric specialisation produces lateralised motor behaviour and left – right perceptual asymmetries (eg Davidson 1995; Vallortigara and Rogers 2005). Recently, it has been suggested that such asymmetries extend to the fine-detail visual speech information: occluding the right side of a talker's mouth attenuates audiovisual integration more than occluding the left side (Nicholls et al 2004a). Here we address a potential left – right asymmetry in visual speech information by examining the natural distribution of gaze fixations during audiovisual speech perception.

Previous studies have shown asymmetries in facial articulation and expression. The right side of the mouth has been shown to have larger motion than the left during speech production (eg Campbell 1982a; Graves et al 1982; Wolf and Goodale 1987; Nicholls and Searle 2006), whereas the left side of the face is more emotionally expressive (eg Campbell 1982b; Borod et al 1988; Nicholls et al 2004b). Studies of

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chimeric faces have revealed asymmetry in both speech and emotion production as well as in facial morphology (eg Gilbert and Bakan 1973; Campbell 1986; Christman and Hackworth 1993; Burt and Perrett 1997). Natural asymmetry of facial features and motion may thus promote asymmetrical viewing patterns.

Previous studies on gaze behaviour in audiovisual speech perception have suggested that asymmetries may exist in information gathering. Observers predominantly direct their gaze toward the right eye of the face (Vatikiotis-Bateson et al 1998; Paré et al 2003), a strategy supporting the right visual hemifield advantage for silent speech-reading (Smeele et al 1998) and audiovisual speech (Baynes et al 1994; Diesch 1995). However, several factors suggest that fixation of specific features may not alter perceptual accuracy. First, kinematic information for individual sounds is spread across the face (Yehia et al 1998) and prosodic information is conveyed by the upper face (Lansing and McConkie 1999) and head movements (Munhall et al 2004a). Second, much of the information in audiovisual speech perception is very low resolution (Vatikiotis-Bateson et al 1994; Munhall et al 2004b), which may preclude the need for foveal processing. Third, evidence suggests that speech intelligibility is not correlated with gaze behaviour. Vatikiotis-Bateson et al (1998) reported that the eyes remain salient even in fairly difficult communicative conditions. Similarly, speech perception accuracy has not been found to be related to mouth fixation during silent speechreading (Lansing and McConkie 2003), McGurk effect (Paré et al 2003), and audiovisual speech studies (Buchan et al 2007). Finally, the use of horizontally mirrored faces has revealed that visual speech perception is not influenced by face orientation (Nicholls and Searle 2006). These factors suggest that face-directed fixations are structured with respect to the observer's viewing preference rather than the faces being viewed.

In the present study, we set out to accomplish three goals. First, we want to quantify the existence of gaze fixation asymmetry in audiovisual speech perception using dynamic stimuli. Many previous studies have focused on face-viewing patterns using static images. However, dynamic speech cues are processed differently from static cues (Munhall et al 2002). Second, we want to test whether these asymmetries are products of the stimulus or the observer. Our recent studies (Everdell et al 2006; Buchan et al 2007) suggest that much of the variance in fixation distribution is accounted for by factors other than those intrinsic to the visual stimulus. Finally, we wish to examine the link between gaze fixation asymmetry and speech intelligibility. The study of Nicholls et al (2004a) suggests that gaze fixation asymmetries are associated with differences in visual speech intelligibility, although other studies show little such correlation (Lansing and McConkie 2003; Paré et al 2003; Buchan et al 2007). No study has explicitly examined biases of gaze fixations. The present study addresses this need.

2 Methods

2.1 *Participants*

Twenty-eight undergraduate students participated in this study (twenty women and eight men; overall mean age $= 20.43 \pm 1.38$ years). All participants spoke English as a first language and had normal hearing and normal or corrected-to-normal vision; twenty-six were right-handed and twenty-two had right-eye dominance. All experimental protocols were approved by the Queen's University Research Ethics Board.

2.2 *Apparatus*

Participants were seated in a single-walled sound booth (Model C-17, Eckel Industries, Morrisburg, ON) with their chin in a chin-rest, such that their eyes were 57 cm from a video monitor (19 inch JVC Model TMH1950CG, 29.97 Hz NTSC, 720×480). Eye position was recorded at 500 Hz with the Eyelink II eye-tracking system (SR Research, Osgoode, ON). Participants performed a 9-point calibration and validation task until the tracking error was reduced to less than 1 deg. Drift correction was performed before each trial.

The eye-tracking system and monitor were interfaced with a Pentium-IV PC and a Pioneer DVD Player (Model V7400). The auditory signal was mixed through a Tucker-Davis System III digital processor, amplified on an InterM R300 reference amplifier and played through speakers (Paradigm Reference Studio 20) on either side of the monitor.

2.3 *Stimuli*

Audiovisual recordings were made of four talkers (two male, two female) saying eight closed-set sentences composed of all possible noun–verb–adverb permutations of the following words: fathers, people (noun); played, walked (verb); quickly, slowly (adverb). All talkers were instructed to speak in an affect-neutral manner. Recordings were edited with Final Cut Pro 4 and lasted from 1704 to 4308 ms (mean $= 2821 \pm 540$ ms). A single-frame image was selected from each recording, when the talker was not speaking, and converted into a static face stimulus lasting 2903 ms. All face stimuli were copied and horizontally mirrored. Faces subtended approximately 17 deg vertically and 12 deg horizontally. Four static images of symmetric, inanimate objects resembling faces (Robert and Robert 1996) were also used to create stimuli lasting 2903 ms, eg a dresser with two top drawers and handles (resembling eyes), one middle drawer (nose), and one bottom drawer (mouth).

Each visual stimulus was accompanied by an auditory target sentence. Dynamic-face stimuli were presented with the congruent sentence, static-face stimuli were accompanied by a sentence said by the depicted talker, and non-face stimuli were coupled with a random sentence. This was counterbalanced between participants, such that each participant heard every talker's voice for every non-face stimulus, but these pairings differed between participants. For all stimuli, a commercial, multi-talker noise signal (Auditec, St. Louis, MO) was mixed in with the audio track.

2.4 *Procedure*

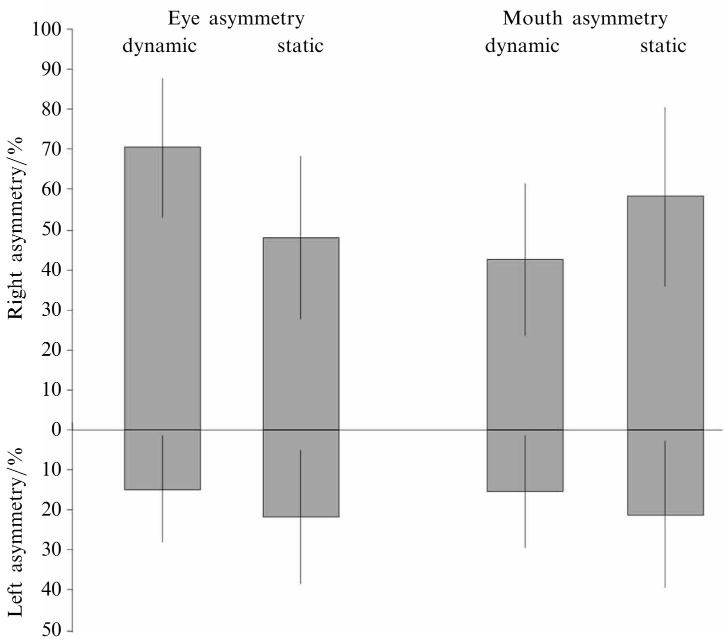
Each trial consisted of a single sentence presented through the speakers accompanied by a visual component presented on the monitor. Participants reported what they heard via a series of three key presses from a set of six potential response keys. Keys were organised into two rows, with the two leftmost keys identifying the two nouns, the middle keys the verbs, and the rightmost keys the adverbs, ie keys were labeled 'fathers', 'walked', etc. Participants were instructed to confine their gaze within the bounds of the video monitor and to report the sentence only once the trials had ended. Responses were scored as correct only if the participants reported the correct sentence with the correct word order; no credit was given for a partially correct answer.

Each participant viewed a total of 112 stimuli (64 dynamic-, 32 static-, and 16 non-face stimuli) presented in a pre-determined randomised order. Each participant viewed the original (non-mirrored) stimuli of two talkers along with the mirrored stimuli of the other two talkers, counterbalanced across participants. Gaze position was recorded online throughout the session.

2.5 *Data analysis*

Instantaneous eye and mouth positions were coded frame-by-frame. The eye reference points were defined as the centre of each pupil. The reference point for the mouth was defined as the centre of four positions: the two corners of the lips and the midlines of the upper and lower lips on the vermilion border. An ellipse was chosen to include the whole face, and was then divided into left and right halves through the half-way point between the eye reference points and the mouth reference point (figure 1a, left panel). Ellipses centred on the reference points were used to delimit the salient facial

(a)



(b)

Figure 1. (a) Distribution of all fixations (left) and of first fixations following stimulus onset (right) for one participant. White contours depict the salient target regions. (b) Percentage of participants (±95% confidence intervals) with significant right (top) and left (bottom) asymmetry for gaze fixations within the eye (left) and mouth (right) regions while viewing dynamic-face and static-face stimuli.

regions considered in this report (figure 1a, right panel). Eye ellipses had a vertical semi-minor axis of 25 pixels and a horizontal semi-major axis of 35 pixels. The mouth ellipse was 15 pixels larger from the reference point than each of the four coded positions, and was divided through the two midline lip positions. Regions within the face-like objects were similarly coded with the use of their eye- and mouth-like features.

Quantitative analyses were conducted on gaze fixations within each of the facial regions described above, for fixations lasting at least 100 ms and for data sets with a minimum of 10 trials. This last criterion severely excluded data from non-face trials; we therefore used a minimum of 6 trials when analysing these data. Non-parametric tests were used whenever the data failed to satisfy the assumption of homogeneity. Fixation data were analysed only between the start and end of the visual stimulus.

To quantify gaze fixation asymmetry, we calculated an asymmetry index using the duration of fixations within corresponding right and left regions: index = (right − left)/(right + left). This index produced positive values for right asymmetry and negative values for left asymmetry (Bryden and Sprott 1981).

3 Results

We tested whether the intelligibility of auditory speech was enhanced by congruent visual speech information by measuring the performance on the speech task with respect to the type of face stimulus presented; dynamic-face trials represented the audiovisual condition, and static-face trials the auditory-only condition. Mean (±SE) percentage correct was 90.2 ± 0.9 in the dynamic-face trials and 60.2 ± 1.0 in the static-face trials. The main effects of stimulus type and talker on performance were significant (two-way ANOVA; stimulus: $F_{1,216} = 231.61$, $p < 0.0001$; talker: $F_{3,216} = 9.47$, $p < 0.0001$), and there was a significant interaction between them ($F_{3,216} = 6.78$, $p = 0.0002$), owing to higher performance with one male talker.

While viewing either static or dynamic face stimuli, participants fixated on the talkers' faces 90.93% of trial time. Figure 1a shows the distribution of one participant's fixations and that of her very first fixation following stimulus onset. Dividing the face stimuli into halves, we found that fixations within the right side of the faces represented the largest proportion (right: 58.7%; left: 41.3%; paired t-test, $t_{27} = 2.20$, $p = 0.032$), and this was already present in the first fixations (right: 62.8%; left: 37.2%; paired t-test, $t_{27} = 3.35$, $p = 0.0015$).

While viewing audiovisual stimuli, participants directed their gaze to the salient facial features (eyes and mouth) for approximately half of all face-directed fixations (51.8%). Considering the duration of fixations within combined left and right salient facial regions across participants and face stimuli, we found a significant bias towards the right side of the talker's face (right: 28.3% of trial time; left: 18.4%; paired t-test, $t_{27} = 2.27$, $p = 0.0317$). Despite this significant right-side fixation bias, a few participants showed significant left asymmetry. Figure 1b shows the proportion of participants whose fixation duration distributions between right and left salient facial regions were statistically different (Wilcoxon signed rank test, $p < 0.05$). These proportions did not vary across face stimulus categories when considering either the eye or mouth regions alone (Fisher exact test, $p = 0.44$). They also did not vary between facial regions (dynamic: $p = 0.68$; static: $p = 1.0$), nor were they related to other laterality measures such as handedness and eye dominance.

We calculated an asymmetry index from the fixations distributed across eye and mouth regions; the median value from each of the participants was used to quantify the magnitude of asymmetry in their fixations. Figure 2 shows the distributions of these median asymmetry indices in both dynamic- and static-face trials. A paired comparison of the absolute index distribution between eye and mouth regions revealed that fixation asymmetry in the eye regions was significantly greater than that of the mouth regions when participants viewed dynamic (Wilcoxon signed rank test, $p = 0.0017$) but not static faces ($p = 0.102$). A significant difference was also observed between dynamic- and static-face trials for asymmetry indices obtained within the eye regions, with participants showing stronger asymmetry during dynamic stimuli ($p = 0.012$). Although different, these asymmetry indices were strongly correlated (Spearman rank correlation test, $r = 0.83$, $p < 0.001$). There was also a significant correlation ($r = 0.46$, $p = 0.047$) between the dynamic and static asymmetry indices calculated from fixations within the mouth regions, but their differences failed to reach significance ($p = 0.067$). The asymmetry indices in the eye and mouth region were also correlated (dynamic: $r = 0.63$, $p < 0.001$; static: $r = 0.52$, $p = 0.036$). In summary, gaze fixation asymmetry

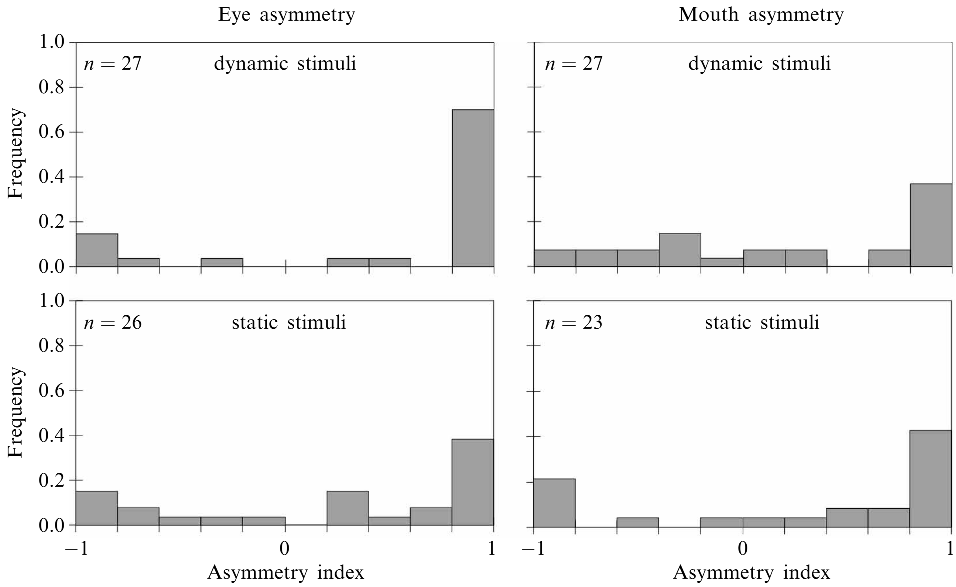


Figure 2. Histograms showing the distribution of median asymmetry indices of the participants' fixations within eye (left) and mouth (right) regions while they viewed dynamic-face (top) and static-face (bottom) stimuli. The number of participants with sufficient data is identified in the top left corner of each histogram. An index value of -1 indicates left asymmetry, while a value of 1 indicates right asymmetry.

was strongest in the eye regions and for dynamic faces, but generally predicted asymmetry in the mouth regions and for static faces.

Did the distribution of gaze fixations impact speech perception? Correlation between task performance and absolute median asymmetry revealed no relationship between performance and the magnitude of fixation asymmetry when participants viewed either dynamic (Spearman rank correlation test; eyes: $r = -0.28$, $p = 0.14$; mouth: $r = -0.09$, $p = 0.64$) or static faces (eyes: $r = 0.13$, $p = 0.51$; mouth: $r = -0.12$, $p = 0.53$). Similar results were obtained when the sign of fixation asymmetry was taken into account ($p > 0.13$), and there was no correlation between the change in performance from static- to dynamic-face stimuli and the corresponding change in asymmetry (eyes: $r = -0.04$, $p = 0.85$; mouth: $r = 0.18$, $p = 0.34$). We also found that the duration of fixations within the mouth region did not predict task performance ($r = -0.09$, $p = 0.064$). Similar results were obtained when considering left ($r = 0.09$, $p = 0.64$) and right ($r = -0.14$, $p = 0.48$) mouth regions as well as the eye regions ($r = 0.02$, $p = 0.91$). Speech perception thus appears independent of the distribution of fixations in this task.

The visual images in half of the trials were horizontally mirrored to test whether fixation asymmetry depended on the characteristics of the face stimuli. Performance in these mirrored trials with either dynamic ($89.1 \pm 1.9\%$) or static faces ($62.4 \pm 2.4\%$) did not differ statistically from the original face trials ($p = 0.39$ and $p = 0.70$, respectively). Figure 3a shows that asymmetry indices obtained in these trials when considering either the eye or the mouth regions were not significantly different (Wilcoxon signed rank test; eyes: $p = 0.94$; mouth: $p = 0.19$). In addition, no significant differences were found between talkers (figure 3b; Friedman test; eyes: $p = 0.38$; mouth: $p = 0.94$). These results strongly support the hypothesis that the asymmetrical distribution of fixations does not simply reflect attributes of the face stimuli.

Participants also viewed face-like objects while listening to the voice of a talker. These non-face trials were contrasted with face trials to test whether fixation asymmetry was limited to viewing human faces. Mean ($\pm$SE) percentage correct in these

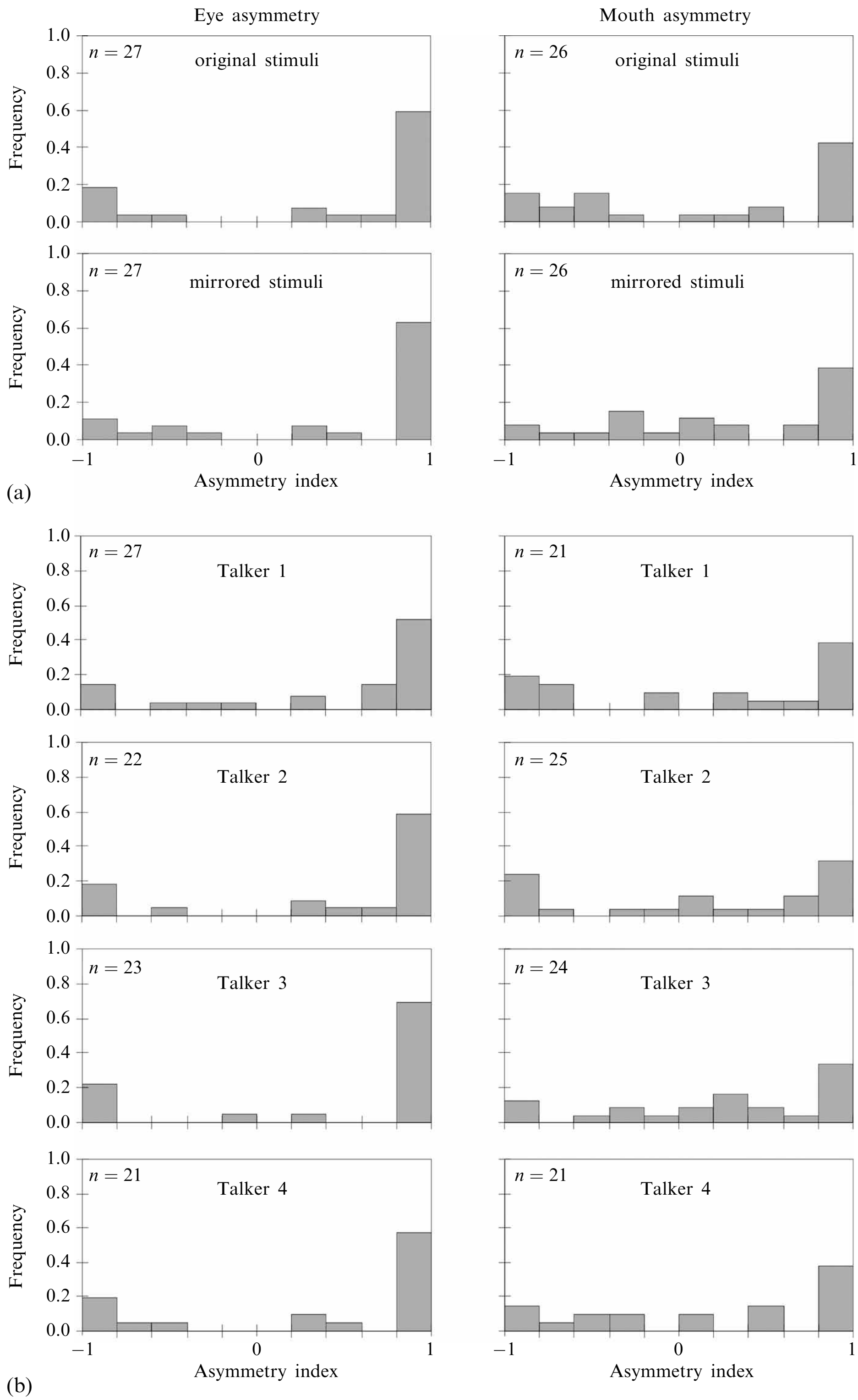


Figure 3. Histograms showing the distribution of median asymmetry indices of the participants' fixations within eye (left) and mouth (right) regions while they viewed original and horizontally mirrored face stimuli (a) as well as all face stimuli from each of the four talkers (b).

trials was 62.9 ± 3.0, a performance significantly less than in dynamic-face trials (paired t-test, $t_{27} = 8.634$, $p < 0.001$) but not different from static-face trials (paired t-test, $t_{27} = -0.396$, $p = 0.70$). There was no significant overall asymmetry for the face-like objects shown by participants who met the inclusion criteria (right = 55.3%; left = 44.6%; paired t-test, $t_{16} = 1.29$, $p = 0.21$). When considering fixations within the 'eye' regions of the stimuli, the absolute median asymmetry indices in non-face trials were significantly smaller than those in all face trials (Wilcoxon signed rank test, $p = 0.016$, df = 11).

4 Discussion

We examined the degree of asymmetry in the distribution of face-directed gaze fixations of humans performing an audiovisual speech perception task and its relationship with speech intelligibility. Participants showed stronger fixation asymmetries while viewing dynamic faces, in comparison to static faces or face-like objects, and especially when they directed their gaze to the talkers' eyes. Although speech perception accuracy was significantly enhanced by the viewing of congruent, dynamic faces, we found no correlation between task performance and gaze fixation asymmetry. Most participants preferentially fixated the right side of the faces and their preferences persisted even when they viewed horizontally mirrored faces, different talkers, or static faces. These results suggest that the asymmetrical distributions of gaze fixations reflect the participants' viewing preferences and not intrinsic facial asymmetries, but that this behavioural bias does not predict correct audiovisual speech perception.

The asymmetry indices for eye and mouth fixations were found to be correlated as well as positively skewed towards a value of one (ie right asymmetry), indicating that fixation asymmetry was consistent within a given participant. This asymmetry was, however, strongest with respect to the eyes. One potential explanation for this is the natural asymmetry of facial motion. Richardson and colleagues (2000) reported that differences in facial enervation cause the right upper part of an expressive face to move most. This interpretation of our data is, however, refuted by the observation that horizontally mirrored faces elicited similar asymmetry (see below). It is more probable that the definition of facial regions led to stronger asymmetry within the eyes. While there was a small gap between the two eye regions, the two halves of the mouth were continuous with each other. Given the resolution limits of the eye-tracking system, fixations near the mouth midline would have been more likely to be categorised incorrectly. That fixation distribution was consistent between the whole face and salient regions further suggests that asymmetry differences between the eye and mouth regions are only quantitative.

Although the majority of participants showed a bias toward the right side of the talkers' faces, some showed no significant asymmetry or left asymmetry. This emphasises the importance of considering individual subjects when measuring asymmetry and deters us from attributing asymmetrical fixation distributions associated with audiovisual speech to a single factor. In general, this behavioural bias of fixating the right side of faces is consistent with a perceptual bias toward the left visual hemifield (eg Luh et al 1991; David 1993; Burt and Perrett 1997). It is reasonable to hypothesise that gaze behaviour during audiovisual speech is under the influence of face processing centres predominantly located within the right hemisphere (eg Moscovitch et al 1976; Benton 1990). Whether individual differences in the degree and sign of face processing lateralisation can account for the degree and sign of gaze fixation asymmetry in audiovisual speech remains unanswered. Evidence from the perception literature suggests, however, that this might well be the case (Butler et al 2005).

The right-side bias in face perception may have developed from extensive face-viewing experience, ie a learned strategy that the right side of the face contains the most information, such as the more pronounced motion of the right side of the mouth during speech (eg Campbell 1982a; Graves et al 1982; Wolf and Goodale 1987; Nicholls and Searle 2006). Besides the contribution of face processing centres in the right hemisphere of the *observer's* brain, cortical areas involved in language production, which are predominantly localised within the left hemisphere of the *talker's* brain, may help explain the asymmetrical gaze fixations in audiovisual speech: intrinsic asymmetrical articulation and motion in the faces of talkers led observers to bias their attention to the right side of all faces. In this view, asymmetry in facial articulation of talkers may have helped promote the observer's asymmetrical viewing patterns, which in turn facilitate visual speech perception by placing facial features within the observer's right visual hemifield (Baynes et al 1994; Diesch 1995; Smeele et al 1998) and thus recruiting speech perception centres within their left hemisphere. One important implication of this interpretation is that, because asymmetry is a learned behaviour, an asymmetry reversal when viewing horizontally mirrored faces would not be expected to occur within the time frame of our experiments.

The reduced fixation asymmetry when participants viewed face-like objects suggests differential processing of human faces. Whether faces present a unique category of stimuli and whether this uniqueness results from nature or nurture is highly debated. One factor overlooked thus far is that reading habits have been shown to influence how observers extract visual information. Indeed, face-viewing biases have been found to correlate with reading biases (Vaid and Singh 1989; but see Gilbert and Bakan 1973) and gaze behaviour differences in audiovisual speech have been observed between Japanese- and English-speaking participants (Vatikiotis-Bateson et al 1998). Our study may be limited by the exclusive use of English-speaking participants, whose left-to-right reading habits may impose a right-side face-viewing bias.

Gaze fixation asymmetry was consistent when participants viewed horizontally mirrored faces and different talkers, strongly refuting the hypothesis that the asymmetrical distribution of fixations is a product of facial asymmetry. Rather, it suggests that asymmetry reflects top – down influences on gaze behaviour, most likely exerted by the lateralised processing of facial and speech information described above, even though visual speech information may also be asymmetrically distributed (eg Nicholls et al 2004a). Given our rather unequivocal results, including the absence of influence of face orientation on audiovisual speech perception (see also Nicholls and Searle 2006), future studies should focus on testing the factors influencing individual fixation asymmetry. Toward that goal, we sought to relate asymmetry with other measures of laterality (handedness and eye dominance), but our negative results—perhaps due to the predominance of right-handed and right-eye-dominant participants—are nevertheless consistent with previous analyses (Borod and Caron 1980; Vaid and Singh 1989). Concurrent assessment of face and language processing laterality may prove more successful.

A major limitation of past studies investigating gaze fixation asymmetry is the use of static images (eg Mertens et al 1993; Butler et al 2005; Leonards and Scott-Samuel 2005). An important result of our study is that gaze fixation asymmetry was best expressed when participants viewed dynamic stimuli, suggesting a better tool for studying face processing. That this asymmetry was statistically stronger during dynamic-face trials only for the eyes is particularly puzzling, given that the mouth exhibits a much greater range of motion and is more important for speech information. This further suggests that gaze asymmetry is not simply a function of facial motion.

The use of dynamic audiovisual stimuli also significantly enhanced speech perception. Nevertheless, the corresponding increase in gaze fixation asymmetry was not correlated with task performance, suggesting that the process of gathering visual speech information is independent of the ability to gather that information. This finding matches the lack of correlation between task performance and time spent looking at mouth observed in both this and other studies (Lansing and McConkie 2003; Buchan et al 2007) and supports the hypothesis that visual speech information gathering is not restricted to high-resolution image processing (Vatikiotis-Bateson et al 1994; Paré et al 2003; Munhall et al 2004b). Overall, despite our observation that the distribution of gaze fixations reflects the observer's viewing preference, which generally conforms with the requirement of the task performed (Lansing and McConkie 1999; Buchan et al 2007), audiovisual integration during speech does not appear to depend on where on a face an observer directs his/her gaze.

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